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Renewable Energy System Selection Based On Computing With Words

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Abstract

Renewable energy is the energy generated from natural resources such as sunlight, wind, rain, tides and geothermal heat. Turkey has a great renewable energy potential with its natural resources such as biomass, geothermal, hydropower, solar, and wind. Selection among energy alternatives is a multicriteria decision-making problem with conflicting and interactive criteria. In this paper, the best energy alternative of Turkey is determined by taking into interactions among criteria by using Choquet integral methodology.

Keywords: Renewable energy, Fuzzy, Decision making, Choquet integral

1. Introduction

Energy is an essential commodity in modern industrial society. It powers our homes, workplaces, transport and communications systems. It is an issue that affects everyone, yet one which is often poorly understood, until an energy crisis arrives. We are clearly living in the midst of an energy crisis that seems unlikely to go away. There is unprecedented concern about fuel prices and oil depletion. There is also a high level of concern about global warming and how best to respond to it. Many people are concerned about these problems and wish to address the symptoms as a matter of urgency, but few understand the basic causes of the problems and consequently fail to realize that fundamental social and technological changes are required to overcome them. As a result of these concerns many nations are attempting to replace conventional power stations with renewable energy systems [1]. Renewable energy is a source of energy that can never be exhausted. We can obtain renewable energy from the sun, water, wind, hot dry rocks, magma, hot water springs and even from firewood, animal manure, crop residues and waste. Main renewable energy resources are biomass energy, hydro energy, geothermal energy, solar energy, and wind energy [2, 3, 4, 5, 6].

Turkey, an energy-importing developing country, presently depends heavily on imported petroleum. The increases in international petroleum prices have affected the Turkish economy adversely, and promise to be the same in the future unless dependence on imported petroleum is reduced by substituting other resources for petroleum. There are many different types of renewable energy that in the longer term should be capable of being harvested to provide a more sustainable energy future. Therefore the determination of the best renewable energy alternative is a vital problem for Turkey.

The selection among renewable energy alternatives is a multicriteria problem with many conflicting criteria.

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Hence, this problem should be solved by a multicriteria decision making method. In the literature some multi criteria decision making (MCDM) techniques such as analytic hierarchy process (AHP) [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19], analytic network process (ANP) [5, 20], the elimination and choice translating reality (ELECTRE) and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) [21, 22, 23, 24], multiple objective linear programming (MOLP) [25, 26] axiomatic design (AD) [7] and Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) [27] have been used for making decisions in energy investments.
The MCDM techniques given above tend to be less effective in dealing with the imprecise or vague nature of the linguistic assessment for Renewable Energy System Selection problem. Under many situations, the values of the qualitative criteria are often imprecisely defined for the decision-makers.

Linguistic variables whose values are not numbers but words or sentences in a natural or artificial language represent crisp information in a form and precision appropriate for the problem. There are decision making situations in which the information cannot be assessed precisely in a quantitative form but may be in a qualitative one, and thus, the use of a linguistic approach is necessary. Choquet integral is a suitable multi-criteria method to capture this imprecise or vague nature by using both linguistic variables and crisp definitions and it is also a flexible aggregation operator. Moreover the Choquet integral is an excellent multi-attribute tool for the problems having interactive attributes under fuzziness.

In this paper, the best energy alternative of Turkey is determined by taking interactions among criteria into account. The main aim of this study is to analyze the interactions between the defined criteria by using Choquet integral methodology. The rest of this study is organized as follows. In Section 2, a literature review on energy problems is presented. The evaluation criteria for renewable energy alternatives are explained in Section 3. Section 4 presents the fundamentals of Choquet integral. In Section 5, a real application for the case of Turkey is performed. Finally, concluding remarks are made in Section 6.

2. Literature Review

Recently some studies have concentrated on making decisions in energy investments. Kahraman et al. [7] used two fuzzy multicriteria decision- making methodologies for the selection among renewable energy alternatives. The first methodology was based on the AHP, while the second was based on AD. In the application of the proposed methodologies the most appropriate renewable energy alternative was determined for Turkey. Lee et al. [28] suggested an integrated multi-criteria decision making (MCDM) approach for the assessment of the optimal alternatives and solutions with the fuzzy theory and AHP, to prioritize the energy technologies of strategic energy technology roadmap. Cai et al. [29] identified optimal strategies in the planning of energy management systems under multiple uncertainties through the development of a fuzzy-random interval programming model. The method was based on an integration of the interval linear programming, superiority–inferiority-based fuzzy-stochastic programming and mixed integer linear programming. Lahdelma et al. [30] considered multi-criteria group decision-making problems, where the decision makers (DMs) want to identify their most preferred alternative(s) based on uncertain or inaccurate criteria measurements. They demonstrated the methods using a decision support model for a retailer operating in the deregulated European electricity market. Ghafghazi et al. [21] evaluated and ranked energy sources available for a case of district heating system in Vancouver, Canada, based on multiple criteria and the points of view of different stakeholders, and to shown how communication would affect the ranking of alternatives. The available energy sources were natural gas, biomass (wood pellets), sewer heat, and geothermal heat. They also used the PROMETHEE method to rank the energy alternatives. Supriyasilp et al. [9] applied Multi-criteria decision analysis to study the potential of develop hydropower projects with electric power greater than 100 kW in the Ping River Basin, Thailand. They determined the advantages and disadvantages of the projects based on five main criteria: electricity generation, engineering and economics, socio-economics, environment, and stakeholder involvement by using AHP. Önüt et al. [20] used analytic network process (ANP) to evaluate the most suitable energy resources for the manufacturing industry. Afgan and Carvalho [31] used a sustainability assessment method for the evaluation of quality of the selected hybrid energy systems. They used the following indicators:

economic indicator, environment indicator, and social indicator. Patlitzianas et al. [32] presented an information decision support system, which consists of an expert subsystem, as well as a multi criteria decision making (MCDM) subsystem. The system supported the state toward the formulation of a modern environment, since it incorporated the ''new parameters'' of the energy market, namely the liberalization and the climate change. The system was successfully applied in the 13 accession member states of the European Union. Begic and Afgan [48] performed the multi-criteria sustainability assessment of various options of the energy power system of Bosnia and Herzegovina in order to investigate options for the selection of new capacity building of this complex system. They compared the rehabilitation of a 110 MW Thermal Power Unit with other options, such as: a thermal power unit with a coal-fueled boiler with combustion in fluidized bed; combined cycle gas turbine plants; hydropower plant, power plants based on solar energy (photovoltaic [PV] systems); wind turbines; and biomass power plants. Burton and Hubacek [34] investigated a local case study of different scales of renewable energy provision for local government in the UK. They compared the perceived social, economic and environmental cost (SEE) of these small-scale energy technologies to larger-scale alternatives. In order to investigate whether the energy could have been generated at a lower SEE cost if large-scale projects had been available, a multi-criteria decision analysis (MCDA) methodology was used to compare the advantages and disadvantages of a number of different renewable energy technologies. They considered eight renewable energy technologies of differing scales: solar photovoltaic, micro-wind, micro hydro, large-scale wind, large-scale hydro, energy from waste, landfill gas and biomass (wood chippings) based on the definition of renewable energy used by the UK government. Patlitzianas et al. [35] presented an integrated multicriteria decision making approach, ordered weighted average, of qualitative judgments for assessing the environment of renewable energy producers in the fourteen different member states of the European Union accession. Afgan et al. [33] presented an evaluation of the potential natural gas utilization in energy sector. They classified the criteria as economic, environmental, social and technological. Among the potential options of gas utilization following systems were considered: Gas turbine power plant, combine cycle plant, Combined Heat and Power plant, steam turbine gas-fired power plant, fuel cells power plant. They also used multi-criteria method, general index of sustainability, for the assessment of potential options with priority given to the economic, environmental, social and technological criteria. Polatidis et al. [36] developed a methodological framework to provide insights regarding the suitability of multi-criteria techniques in the context of renewable energy planning. They created a comparative matrix with the various appropriate multi-criteria techniques and their performance for renewable energy planning. Zhou et al. [37] surveyed on decision analysis (DA) in energy and environmental modeling. They found that the number of publications was almost 252. They also extended and refined survey by classifying the 252 studies by source of publication, DA method, application area, and several new attributes. Statistical analyses using hypothesis testing and a multiple attribute analysis on the suitability of different DA methods in each application area were conducted. It was found that the importance of multiple criteria decision-making methods and energy-related environmental studies has increased substantially since 1995. Ulutaş [5] analyzed the energy policy problem as a MCDM problem with interactive criteria and alternatives. She used the ANP to evaluate the alternative energy sources for Turkey's energy resources. Cavallaro and Ciraolo [38] proposed a multicriteria method in order to support the selection and evaluation of one or more of the solutions to make a preliminary assessment regarding the feasibility of installing some wind energy turbines in a site on the island of Salina in Italy. They compared the four wind turbine configurations. They used a multicriteria algorithm to rank the solutions. Pohekar and Ramachandran [39] analyzed several methods based on weighted averages, priority setting, outranking, fuzzy principles and their combinations and employed for energy planning decisions. They presented a review of more than 90 published papers to analyze the applicability of the methods. It was observed that Analytical Hierarchy Process (AHP) is the most popular technique followed by outranking techniques PROMETHEE and The elimination and choice translating reality (ELECTRE). Topcu and Ulengin [40] focused on the multi-attribute decision making evaluation of energy resources that enabled the selection of the most suitable electricity generation alternative for Turkey. They also provided an integrated decision aid (IDEA) framework for the selection of the most suitable multi-attribute method and presented ranking of alternatives. Polatidis and Haralambopoulos [41] presented the experience from a number of consultations with stakeholders involved in renewable energy projects, the difficulties that have risen and they proposed a new methodological framework of multi-participatory and multi-criteria decision-making. They examined a number of case studies in order to formulate a new regulatory framework and concentrated on renewable energy scene in Greece. Beccali et al. [42] analyzed an application of the multicriteria decision-making methodology used to assess an action plan for the diffusion of renewable energy technologies at regional scale. They also carried out a case study for the island of Sardinia. They used ELECTRE-III method with fuzzy environment. Borges and Antunes [26] presented an interactive approach to deal with fuzzy multiple objective linear programming problems based on the analysis of the decomposition of the parametric diagram into indifference regions corresponding to basic efficient solutions. The approach was illustrated to tackle uncertainty and imprecision associated with the coefficients of an input–output energy-economy planning model, aimed at providing decision support to decision makers in the study of the interactions between the energy system and the economy on a national level. Goletsis et al. [22] combined group techniques with multicriteria methods in an integrated methodology so as the prioritization of project proposals in the energy sector of Armenia. They developed Multicriteria Ranking Method (MURAME), a hybrid of ELECTRE III and PROMETHEE methods, and constituted the main part of an integrated project ranking methodology for groups. Haralambopoulos and Polatidis [24] described an applicable group decision-making framework for assisting with multi-criteria analysis in renewable energy projects, utilizing the PROMETHEE II outranking method to achieve group consensus in renewable energy projects. The proposed framework was tested in a case study concerning the exploitation of a geothermal resource, located in the island of Chios, Greece. Afgan and Carvalho [43] presented the selection of criteria and options for the new and renewable energy technologies assessment based on the analysis and synthesis of parameters under the information deficiency method to define energy indicators used in the assessment of energy systems which met the sustainability criterion. They took into account energy resources, environment capacity, social indicators and economic indicators. Goumas and Lygerou [23] extended a multicriteria method of ranking alternative projects, PROMETHEE, to deal with fuzzy input data. The proposed method was applied for the evaluation and ranking of alternative energy exploitation schemes of a low temperature geothermal energy.

3. Evaluation Criteria for Selection of the best Alternative

Beccali et al. [42] used ELECTRE to assess an action plan for the diffusion of renewable energy technologies at regional scale. They identified 3 main and 12 submain criteria as follows:

(i) Technological criteria
- (a) Targets of primary energy saving in regional scale
- (b) Technical maturity, reliability
- (c) Consistence of installation and maintenance requirements with local technical know-how
- (d) Continuity and predictability of performances
- (e) Cost of saved primary energy

(ii) Energy and environmental criteria
- (f) Sustainability according to greenhouse pollutant emissions
- (g) Sustainability according to other pollutant emissions
- (h) Land requirement
- (i) Sustainability according to other environmental impacts

(iii) Social and economic criteria
- (a) Labour impact
- (b) Market maturity
- (c) Compatibility with political, legislative and administrative situation

Goletsis et al. [22] studied the energy planning process to rank the projects. They took into account the criteria as follows:

(i) Socio-political
- (a) Consistency of the Project with the national energy policy objectives
- (b) Political acceptance of the project
- (c) Social acceptance of the project
- (d) Scope of the project vs. needs to be satisfied-urgency
- (e) Appropriateness of the implementing organizations

(ii) Economic
- (a) Estimated full cost of the project

(iii) Technical
- (a) Technical feasibility

(b) Technical risk
(c) Access to technology by local agents
(d) Mastering of the technology by the local agents (maturity of projects)
(e) Readiness of the local agents to implement the project
(f) Multiplicative effects on the local technology basis

(iv) Environmental
(a) Environmental impact

Topcu and Ulengin [40] concerned with the multi-attribute decision making evaluation of energy resources that enable the selection of a suitable electricity generation alternative for Turkey. They analyzed possible energy alternatives based on their physical, environmental, economical, and political and other uncontrollable aspects. In this paper the main and sub criteria in Table 1 which are obtained by taking into account the above works and Kahraman et al. [7] are used to evaluate renewable energy alternatives.

Table 1. Criteria taken into account to select the most appropriate renewable energy alternative

Main Criteria	Sub-Criteria
C1: Technological	C11: Feasibility C12: Risk C13: Reliability C14: The duration of preparation phase C15: The duration of implementation phase C16: Continuity and predictability of performance C17: Local technical know how
C2: Environmental	C21: Pollutant emission C22: Land requirements C23: Need of waste disposal
C3: Socio-Political	C31: Compatibility with the national energy policy objectives C32: Political acceptance C33: Social acceptance C34: Labour impact
C4: Economic	C41: Implementation cost C42: Availability of funds C43: Economic value (PW, IRR, B/C)

4. Choquet Integral

Choquet integral is a method which measures the expected utility of an uncertain event and it is the generalization of the weighted average method, the Ordered Weighted Average operator, and the max–min operator. A fuzzy integral is a sort of general averaging operator that can represent the notions of importance of a criterion and interactions among criteria. The most important feature of a fuzzy integral is its ability to represent a certain kind of interaction among criteria, ranging from redundancy (negative interaction) to synergy (positive interaction). The disadvantage of fuzzy integral is the complexity of the model, since the number of coefficients involved in a fuzzy integral model grows exponentially with the number of criteria to be aggregated. The main difficulty is to identify all these coefficients, either by some learning data, or by a questionnaire, or both. To define fuzzy integrals, a set of values of importance is needed. This set is composed of the values of a fuzzy measure. So, a value of importance for each subset of attributes is needed [44].

The success of a Choquet integral depends on an appropriate representation of fuzzy measures, which captures the importance of individual criterion or their combination. In this paper, the generalized Choquet integral proposed by Auephanwiriyakul et al. [44] will be used, in which measurable evidence is represented in terms of intervals, whereas fuzzy measures are real numbers, is an extension of the standard Choquet integral. In contrast to Auephanwiriyakul et al. [44], Tsai and Lu [45] proposes another generalization that involves linguistic expressions as well as information fusion between criteria to overcome vagueness and imprecision of linguistic terms in questionnaires.

The methodology is composed of eight steps [45]:

Step 1. Given criterion i, respondents' linguistic preferences for the degree of importance, perceived performance levels of alternatives, and tolerance zone are surveyed.

Step 2. In view of the compatibility between perceived performance levels and the tolerance zone, trapezoidal fuzzy numbers are used to quantify all linguistic terms in this study. Given respondent t and criteria i, linguistic terms for the degree of importance is parameterized by

$\tilde{A}_i^t = \left(a_{i1}^t, a_{i2}^t, a_{i3}^t, a_{i4}^t\right)$, perceived performance levels by $\tilde{p}_i^t = \left(p_{i1}^t, p_{i2}^t, p_{i3}^t, p_{i4}^t\right)$, and the tolerance zone by $\tilde{e}_i^t = \left(e_{i1L}^t, e_{i2L}^t, e_{i3U}^t, e_{i4U}^t\right)$. In this case study, t=1,2,3,4,5, i=1,2,…,n_j, j=1,2,3,4, n_1=3, n_2=2, n_3=4, n_4=3; where n_j represents the number of criteria in dimension j.

Step 3. Average $\tilde{A}_i^t$, $\tilde{p}_i^t$ and $\tilde{e}_i^t$ into $\tilde{A}_i$, $\tilde{p}_i$, and $\tilde{e}_i$, respectively using Eq. (1).

$$\tilde{A}_i = \frac{\sum_{t=1}^{k} \tilde{A}_i^t}{k} = \left(\frac{\sum_{t=1}^{k} a_{i1}^t}{k}, \frac{\sum_{t=1}^{k} a_{i2}^t}{k}, \frac{\sum_{t=1}^{k} a_{i3}^t}{k}, \frac{\sum_{t=1}^{k} a_{i4}^t}{k} \right) \quad (1)$$

Step 4. Normalize the value of each criterion using Eq. (2).

$$\tilde{f}_i = \underset{\alpha\in[0,1]}{\|} \bar{f}_i^{\alpha} = \underset{\alpha\in[0,1]}{\|} [f_{i,\alpha}^-, f_{i,\alpha}^+] \quad (2)$$

where $f_i \in F(S)$ is a fuzzy-valued function. $\tilde{F}(S)$ is the set of all fuzzy-valued functions $f, f_i^{\alpha} = \left[f_{i,\alpha}^-, f_{i,\alpha}^+\right] = \dfrac{\bar{p}_i^{\alpha} - \bar{e}_i^{\alpha} + [1,1]}{2}, \bar{p}_i^{\alpha}$ and $\bar{e}_i^{\alpha}$ are α-level cuts of $\tilde{p}_i$ and $\tilde{e}_i$ for all $\alpha = [0,1]$.

Step 5. Calculate the value of dimension *j* using Eq. (3).

$$(C)\int \tilde{f} d\tilde{g} = \underset{\alpha=[0,1]}{\|} \left[(C)\int f_{\alpha}^- dg_{\alpha}^-, (C)\int f_{\alpha}^+ dg_{\alpha}^+,\right] \quad (3)$$

where
$\bar{g}_i : P(S) \rightarrow I(R^+), \bar{g}_i = [g_i^-, g_i^+]$,
$\bar{g}_i^{\alpha} = [g_{i,\alpha}^-, g_{i,\alpha}^+]$, $\bar{f}_i : S \rightarrow I(R^+)$, and
$f_i = [f_i^-, f_i^+]$ for i=1, 2, 3, ..., n_j.

To be able to calculate this value, a λ value and the fuzzy measures $g(A_{(i)})$, i=1,2,...,n, are needed. These are obtained from Eqs. (4-6) [46, 47]

$$g\left(A_{(n)}\right) = g\left(\left\{s_{(n)}\right\}\right) = g_n \quad (4)$$

$$g\left(A_{(i)}\right) = g_i + g\left(A_{(i+1)}\right) + \lambda g_i g\left(A_{(i+1)}\right) \quad \text{where } 1 \le i < n \quad (5)$$

$$1 = g(S) = \begin{cases} \frac{1}{\lambda}\left\{\prod_{i=1}^{n}\left[1 + \lambda g(A_i)\right] - 1\right\} & \text{if } \lambda \ne 0 \\ \sum_{i=1}^{n} g(A_i) & \text{if } \lambda = 0 \end{cases} \quad (6)$$

where, $A_i \cap A_j = \phi$ for all i, j = 1,2,3,…,n and $i \ne j$, and $\lambda \in (-1, \infty]$.

Step 6. Aggregate all dimensional performance levels of the alternatives into overall performance levels, using a hierarchical process applying the two-stage aggregation process of the generalized Choquet integral. This is represented in Eq. (7). The overall performance levels yields a fuzzy number, $\tilde{V}$.

$$\left.\begin{matrix} main\ criterion_{(1)} = (C)\int fdg \\ \vdots \\ main\ criterion_{(m)} = (C)\int fdg \end{matrix}\right\rangle \; V = (\mathrm{C})\int main\ criterion\ dg \quad (7)$$

Step 7. Assume that the membership of $\tilde{V}$ is $\mu_{\tilde{V}}(x)$; defuzzify the fuzzy number $\tilde{V}$ into a crisp value *v* using Eq. (8) and make a comparison of the overall performance levels of alternatives.

$$F\left(\tilde{A}\right) = \frac{a_1 + a_2 + a_3 + a_4}{4} \quad (8)$$

Step 8. Compare weak and advantageous criteria among the alternatives using Eq. (2).

5. An Illustrative Example

In this section, the most suitable renewable energy alternative for Turkey is determined based on the Choquet integral methodology. Biomass, Geothermal, Hydropower, Solar, and Wind energies are the potential renewable energy sources for Turkey.

Step 1. The criteria given in Table 1 are selected from the literature to evaluate the alternatives. The assessments of the alternatives are presented in Table 2 and Table 3.

The importances of the criteria are calculated by using analytic hierarchy process and all values given in Table 3 are taken from the literature [7]

Step 2. Trapezoidal fuzzy numbers given in Table 2 are transformed into standard trapezoidal numbers as in Table 4.

Step 3. The aggregation procedure is done by using Eq. 1. To illustrate the aggregation phase, an illustrative example for Wind energy is given in Table 4.

Table 2. Linguistic evaluation for alternatives

		Biomass				Geothermal				Hydropower				Solar				Wind			
		E1	E2	E3	E4	E1	E2	E3	E4	E1	E2	E3	E4	E1	E2	E3	E4	E1	E2	E3	E4
Technological	**C_{11}**	G	7	8	A7	G	7	7	A6	G	7	6~8	A6	P	1	3~4	A4	G	5	7~8	A8
	C_{12}	VL	7	8	8	7	7	6~8	7	7	7	6~8	7	VL	8	8~9	9~10	VL	8	8~9	9~10
	C_{13}	7~8	8	8	7	7~8	8	7~8	7~8	8	8	7~8	7	9	8	8	9	9	8	8	9
	C_{14}	7~8	7	8	7~8	7	7	8~9	7~8	8	6	8~9	7~8	8	7	8	7~9	8	7	8	7~9
	C_{15}	8	7	7	VG	7	7	7	G	7	7	6~7	G	3	2	2~3	G	5	2	2~3	G
	C_{16}	G	7	8~9	7	VG	8	8	8	G	7	5~6	7	VG	8	8~9	8	VG	8	8~9	8
	C_{17}	G	7	8~10	A7	G	9	8	A9	G	6	8~10	A7	P	1	1~2	A4	G	4	4~5	A7
Environmental	**C_{21}**	G	G	8	A8	VH	7	7	A4	L	9	7	A9	VL	9	8~9	A9	VL	9	8~9	A9
	C_{22}	8	7	8~9	8	G	8	7~8	7	G	5	5~7	7	VL	8	9	8	VL	8	9	8
	C_{23}	G	8	G	7~8	VG	8	7~8	7	L	5	6	6~7	VG	8	9	8~9	VG	8	9	8~9
Economic	**C_{31}**	G	4	7	A8	G	8	8	A6	G	5	6	A6	VH	2	1~2	A2	VH	4	4~5	A5
	C_{32}	G	4	7	8	G	9	8~9	8	VG	8	6	8	VG	8	8~9	8	VG	8	8~9	8
	C_{33}	G	5	8	7	G	8	7~8	7	G	7	6	7~8	VG	8	8~9	7	VG	8	8~9	7~8
Socio-Political	**C_{41}**	8	8~9	8	8	8	9	8~9	8	8	7	8	8	9	9	9~10	8	9	9	9~10	8
	C_{42}	VH	8	9	G	G	8	8	VG	VG	7	8	G	VH	9	10	VH	VH	9	10	VH
	C_{43}	VH	9	9	7	G	9	9	8	VG	9	9	8	VH	9	10	10	VH	9	10	10
	C_{44}	G	8	G	8	G	8	7	8	G	7	7	8	G	4	9~10	8	G	4	9~10	8

Table 3. Individual importances of criteria and the tolerance intervals

Criteria	Sub criteria	Individual Importances	Tolerance Zone
Technological		0.44	
	Feasibility	0.106	(7.50,10.00,10.00)
	Risk	0.335	(7.50,10.00,10.00)
	Reliability	0.241	(7.50,10.00,10.00)
	The duration of preparation phase	0.043	(7.50,10.00,10.00)
	The duration of implementation phase	0.037	(5.00,10.00,10.00)
	Continuity and predictability of performance	0.108	(7.50,10.00,10.00)
	Local technical know how	0.130	(5.00,10.00,10.00)
Environmental		0.411	
	Pollutant emission	0.507	(7.50,10.00,10.00)
	Land requirements	0.074	(7.50,10.00,10.00)
	Need of waste disposal	0.420	(7.50,10.00,10.00)
Economic		0.084	
	Implementation cost	0.161	(4.00,10.00,10.00)
	Availability of funds	0.291	(7.50,10.00,10.00)
	Economic value (PW, IRR, B/C)	0.548	(7.50,10.00,10.00)
Socio-Political		0.064	(7.50,10.00,10.00)
	Compatibility with the national energy policy objectives	0.629	
	Political acceptance	0.116	(7.50,10.00,10.00)
	Social acceptance	0.143	(7.50,10.00,10.00)
	Labour impact	0.111	(7.50,10.00,10.00)

Table 4. Scores and Converted STFN for Biomass

Renewable Energy Evaluation Criteria		Expert-1 (E1)		Expert-2 (E2)		Expert-3 (E3)			Expert-4 (E4)			Aggregated STFN
		Score	STFN	Score	STFN	Score		STFN	Score		STFN	
Technological	Feasibility	G	(5, 7.5, 7.5, 10)	5	(5, 5, 5, 5)	7	8	(7, 7, 8, 8)	About	8	(7, 8, 8, 9)	(6, 6.875, 7.125, 8)
	Risk	VL	(7.5, 10, 10, 10)	8	(8, 8, 8, 8)	8	9	(8, 8, 9, 9)	9		(9, 9, 10, 10)	(8.125, 8.75, 9.25, 9.25)
	Reliability	9	(9, 9, 10, 10)	8	(8, 8, 8, 8)	8	8	(8, 8, 8, 8)	9	9	(9, 9, 9, 9)	(8.5, 8.5, 8.75, 8.75)
	The duration of preparation phase	8	(7, 8, 8, 9)	7	(7, 7, 7, 7)	8	8	(8, 8, 8, 8)	7	9	(7, 7, 9, 9)	(7.25, 7.5, 8, 8.25)
	The duration of implementation phase	5	(4, 5, 5, 6)	2	(2, 2, 2, 2)	2	3	(2, 2, 3, 3)		G	(5, 7.5, 7.5, 10)	(3.25, 4.125, 4.375, 5.25)
	Continuity and predictability of performance	VG	(7.5, 10, 10, 10)	8	(8, 8, 8, 8)	8	9	(8, 8, 9, 9)	8	8	(8, 8, 8, 8)	(7.875, 8.5, 8.75, 8.75)
	Local technical know how	G	(5, 7.5, 7.5, 10)	4	(4, 4, 4, 4)	4	5	(4, 4, 5, 5)	About	7	(6, 7, 7, 8)	(4.75, 5.625, 5.875, 6.75)
Environmental	Pollutant emission	VL	(7.5, 10, 10, 10)	9	(9, 9, 9, 9)	8	9	(8, 8, 9, 9)	A	9	(8, 9, 9, 10)	(8.125, 9, 9.25, 9.5)
	Land requirements	VL	(7.5, 10, 10, 10)	8	(8, 8, 8, 8)	9	9	(9, 9, 9, 9)	8	8	(8, 8, 8, 8)	(8.125, 8.75, 8.75, 8.75)
	Need of waste disposal	VG	(7.5, 10, 10, 10)	8	(8, 8, 8, 8)	9	9	(9, 9, 9, 9)	8	9	(8, 8, 9, 9)	(8.125, 8.75, 9, 9)
Economic	Implementation cost	VH	(0, 0, 0, 2.5)	4	(4, 4, 4, 4)	4	5	(4, 4, 5, 5)	About	5	(4, 5, 5, 6)	(3, 3.25, 3.5, 4.375)
	Availability of funds	VG	(7.5, 10, 10, 10)	8	(8, 8, 8, 8)	8	9	(8, 8, 9, 9)	8	8	(8, 8, 8, 8)	(7.875, 8.5, 8.75, 8.75)
	Economic value (PW, IRR, B/C)	VG	(7.5, 10, 10, 10)	8	(8, 8, 8, 8)	8	9	(8, 8, 9, 9)	7	8	(7, 7, 8, 8)	(7.625, 8.25, 8.75, 8.75)
Socio-Political	Compatibility with the national energy policy objectives	9	(8, 9, 9, 10)	9	(9, 9, 9, 9)	9	10	(9, 9, 10, 10)	8	8	(8, 8, 8, 8)	(8.5, 8.75, 9, 9.25)
	Political acceptance	VH	(7.5, 10, 10, 10)	9	(9, 9, 9, 9)	10		(10, 10, 10, 10)	VH		(7.5, 10, 10, 10)	(8.5, 9.75, 9.75, 9.75)
	Social acceptance	VH	(7.5, 10, 10, 10)	9	(9, 9, 9, 9)	10		(10, 10, 10, 10)	#	#	(10, 10, 10, 10)	(9.125, 9.75, 9.75, 9.75)
	Labour impact	G	(5, 7.5, 7.5, 10)	4	(4, 4, 4, 4)	9	10	(9, 9, 10, 10)	8	8	(8, 8, 8, 8)	(6.5, 7.125, 7.375, 8)

Table 5. Calculated values

	Biomass	Geothermal	Hydropower	Solar	Wind
Overall Values	(0.343,0.384,0.391,0.546)	(0.372,0.396,0.407,0.558)	(0.355,0.38,0.386,0.535)	(0.402,0.429,0.44,0.579)	(0.41,0.432,0.445,0.584)
C1	(0.358,0.376,0.386,0.521)	(0.351,0.367,0.389,0.547)	(0.329,0.346,0.369,0.532)	(0.337,0.362,0.379,0.541)	(0.367,0.392,0.41,0.571)
C11	(0.325,0.369,0.369,0.538)	(0.3,0.344,0.344,0.513)	(0.288,0.331,0.356,0.525)	(0.088,0.131,0.144,0.313)	(0.3,0.344,0.356,0.525)
C12	(0.381,0.413,0.413,0.538)	(0.325,0.338,0.363,0.5)	(0.325,0.338,0.363,0.5)	(0.406,0.438,0.463,0.588)	(0.406,0.438,0.463,0.588)
C13	(0.35,0.35,0.363,0.488)	(0.363,0.363,0.4,0.525)	(0.363,0.363,0.388,0.513)	(0.425,0.425,0.438,0.563)	(0.425,0.425,0.438,0.563)
C14	(0.35,0.35,0.388,0.513)	(0.363,0.363,0.4,0.525)	(0.35,0.35,0.388,0.513)	(0.363,0.375,0.4,0.538)	(0.363,0.375,0.4,0.538)
C15	(0.356,0.4,0.4,0.663)	(0.325,0.369,0.369,0.663)	(0.3,0.344,0.356,0.65)	(0.138,0.181,0.194,0.488)	(0.163,0.206,0.219,0.513)
C16	(0.338,0.369,0.381,0.538)	(0.394,0.425,0.425,0.55)	(0.3,0.331,0.344,0.5)	(0.394,0.425,0.438,0.563)	(0.394,0.425,0.438,0.563)
C17	(0.394,0.425,0.438,0.563)	(0.375,0.419,0.419,0.713)	(0.313,0.356,0.381,0.675)	(0.063,0.106,0.119,0.413)	(0.238,0.281,0.294,0.588)
C2	(0.333,0.398,0.404,0.579)	(0.335,0.372,0.379,0.512)	(0.319,0.357,0.364,0.527)	(0.406,0.444,0.455,0.587)	(0.406,0.444,0.455,0.587)
C21	(0.344,0.419,0.419,0.588)	(0.306,0.35,0.35,0.488)	(0.363,0.406,0.406,0.575)	(0.406,0.45,0.463,0.6)	(0.406,0.45,0.463,0.6)
C22	(0.375,0.388,0.4,0.538)	(0.338,0.369,0.381,0.538)	(0.275,0.306,0.331,0.488)	(0.406,0.438,0.438,0.563)	(0.406,0.438,0.438,0.563)
C23	(0.313,0.375,0.388,0.575)	(0.369,0.4,0.413,0.538)	(0.275,0.306,0.319,0.475)	(0.406,0.438,0.45,0.575)	(0.406,0.438,0.45,0.575)
C3	(0.302,0.335,0.340,0.527)	(0.346,0.38,0.397,0.583)	(0.321,0.354,0.361,0.538)	(0.332,0.36,0.379,0.539)	(0.419,0.344,0.406,0.575)
C31	(0.288,0.331,0.344,0.688)	(0.325,0.369,0.369,0.713)	(0.263,0.306,0.306,0.65)	(0.05,0.063,0.075,0.419)	(0.361,0.332,0.36,0.538)
C32	(0.3,0.331,0.331,0.488)	(0.375,0.406,0.419,0.575)	(0.369,0.4,0.4,0.525)	(0.394,0.425,0.438,0.563)	(0.306,0.05,0.063,0.65)
C33	(0.313,0.344,0.356,0.513)	(0.338,0.369,0.394,0.55)	(0.313,0.344,0.356,0.513)	(0.381,0.413,0.438,0.563)	(0.4,0.394,0.425,0.525)
C4	(0.381,0.408,0.423,0.567)	(0.388,0.411,0.419,0.563)	(0.373,0.397,0.397,0.537)	(0.418,0.441,0.451,0.587)	(0.418,0.441,0.451,0.587)
C41	(0.388,0.4,0.425,0.563)	(0.4,0.413,0.425,0.563)	(0.375,0.388,0.388,0.525)	(0.425,0.438,0.45,0.588)	(0.425,0.438,0.45,0.588)
C42	(0.369,0.431,0.431,0.588)	(0.356,0.419,0.419,0.575)	(0.344,0.406,0.406,0.563)	(0.425,0.488,0.488,0.613)	(0.425,0.488,0.488,0.613)
C43	(0.406,0.438,0.438,0.563)	(0.388,0.419,0.419,0.575)	(0.419,0.45,0.45,0.575)	(0.456,0.488,0.488,0.613)	(0.456,0.488,0.488,0.613)
C44	(0.325,0.388,0.388,0.575)	(0.35,0.381,0.381,0.538)	(0.338,0.369,0.369,0.525)	(0.325,0.356,0.369,0.525)	(0.325,0.356,0.369,0.525)

Step 4. By using Eq. (2), the evaluation values are normalized for each criterion.

Step 5. At different α-levels, the values of all criteria in the same dimension are aggregated by using Eq. (3). To illustrate the calculation procedure in Steps 4 and 5, an example is given for *Wind energy* alternative under *environmental criterion*. Using Eq. (2),

$$f, f_i^{\alpha} = \left[f_{1,0}^{-}, f_{1,0}^{+}\right]$$

$$= \frac{\left[(8.125/10), (9.5/10)\right] - \left[(7.5/10), (10/10)\right] + \left[1, 1\right]}{2}$$

$$= \left[0.406, 0.6\right]$$

$$\left[f_{2,0}^{-}, f_{2,0}^{+}\right] = [0.406, 0.563]$$

$$\left[f_{3,0}^{-}, f_{3,0}^{+}\right] = [0.406, 0.575]$$

are obtained.

Their corresponding degrees of importances are $\bar{g}_1{}^0 = 0.161$, $\bar{g}_2{}^0 = 0.292$, and $\bar{g}_3{}^0 = 547$, respectively. First, the sequence $f_{i,0}{}^-$ is sorted, where i=1, 2 and 3, as follows: $f_{2,0}^- < f_{3,0}^- < f_{1,0}^-$. By solving equation $0 = \frac{1}{\lambda}\left\{\prod_{i=1}^{3}[1+\lambda \bar{g}_i] - 1\right\}$, λ=0 is obtained. Then, their fuzzy measures are derived as follows;

g(A(3)) = g3 = 0.161
g(A(2)) = g2 + g(A(3)) + λ g2 g(A(3)) = 0.709
g(A(1)) = g1 + g(A(2)) + λ g1 g(A(2)) = 1

The aggregated Choquet integral value for the surface criterion is calculated as

$$(C)\int \tilde{f} d\tilde{g} = \left[0.406,\ 0.575\right]$$

Step 6. Smilar to Steps 4 and 5, the overall values are obtained for all alternatives, as shown in Table 5.

Step 7. From Table 5, the defuzzified overall values of alternatives using generalized Chouqet Integral are obtained as 0.416, 0.433, 0.414, 0.462, and 0.468 (Table 6). So, Wind energy is the best alternative for energy investment of Turkey.

Step 8. Weak and advantageous criteria of the alternatives are presented in Table 6 by asterix. The numbers highlighted by asterix in Table 6 represents that the alternative has more advantage than the others for the related criterion.

Table 6. The defuzzified values

	Defuzzified Values				
	Biomass	Geothermal	Hydropower	Solar	Wind
Overall Values	0.416	0.433	0.414	0.462	**0.468**
C1	0.410	0.414	0.394	0.405	0.435*
C11	0.400*	0.375	0.375	0.169	0.381
C12	0.436	0.381	0.381	0.473*	0.473*
C13	0.388	0.413	0.406	0.463*	0.463*
C14	0.400	0.413	0.4	0.419*	0.419*
C15	0.455*	0.431	0.413	0.25	0.275
C16	0.407	0.448	0.369	0.455*	0.455*
C17	0.455*	0.481	0.431	0.175	0.35
C2	0.429	0.399	0.392	0.473*	0.473*
C21	0.443	0.373	0.438	0.48*	0.48*
C22	0.425	0.406	0.35	0.461*	0.461*
C23	0.413	0.43	0.344	0.467*	0.467*
C3	0.428	0.427	0.394	0.403	0.436*
C31	0.413	0.444*	0.381	0.152	0.398
C32	0.363	0.444*	0.423	0.455	0.267
C33	0.382	0.413	0.381	0.448*	0.436
C4	0.445	0.445	0.426	0.474*	0.474*
C41	0.444	0.45	0.419	0.475*	0.475*
C42	0.455	0.442	0.43	0.503*	0.503*
C43	0.461	0.45	0.473	0.511*	0.511*
C44	0.419*	0.413	0.4	0.394	0.394

According to Table 6, the scores of the alternatives are 0.416, 0.433, 0.414, 0.462, and 0.468 and the rank of the alternatives from the best to the worst is Wind, Solar, Geothermal, Biomass, and Hydropower, respectively. Hence, the best energy alternative for energy investment in Turkey is Wind energy. The wind energy alternative has also the best scores for most of the criteria. The second best alternative is solar energy. Moreover, performance scores of solar energy and wind energy are the same with respect to most of the criteria (Table 6). Since the wind energy is better than solar energy in terms of knowhow, implementation cost, and feasibility, it is the best alternative for energy investments in Turkey.

6. Conclusions

Turkey has a great renewable energy potential with its natural resources such as biomass, geothermal, hydropower, solar, and wind. Therefore, Turkish government encourages the commercial investments in renewable energy sector by publishing new energy issues. To maximize the benefit from energy alternatives, sources of the country must be carefully used. Therefore it is important to determine the rank of the energy alternatives of Turkey. In this paper, Choquet integral methodology is used to determine the rank of alternatives. According to the obtained results, the wind energy is the best alternative for Turkey. Wind, Solar, Geothermal, Biomass, and Hydropower is the rank from the best to the worst, respectively.

For further research, ANP is suggested to take the internal and external dependencies among criteria. ANP can also be handled under fuzzy environment to process the linguistic evaluations for energy alternatives and criteria.

References

1. P. Jennings, New directions in renewable energy education, *Renewable Energy* **34** (2009) 435–439.
2. K. Kaygusuz, Environmental impacts of energy utilisation and renewable energy policies in Turkey, Energy Policy **30** (2002) 689–698.
3. K. Kaygusuz, Renewable and sustainable energy use in Turkey: a review, Renewable and Sustainable Energy Reviews **6** (2002) 339–366.
4. K. Kaygusuz, Energy policy and climate change in Turkey, Energy Conversion and Management **44** (2003) 1671–1688.
5. B. H. Ulutaş, Determination of the appropriate energy policy for Turkey, *Energy* 30 (2005) 1146–1161.
6. A. Demirbaş, Importance of biomass energy sources for Turkey, Energy Policy **36** (2008) 834–842.
7. C. Kahraman, İ. Kaya, S. Çebi, A comparative analysis for multiattribute selection among renewable energy alternatives using fuzzy axiomatic design and fuzzy analytic hierarchy process, Energy **34** (2009) 1603–1616.
8. A.H.I. Lee, H.H. Chen and H.Y. Kang, Multi-criteria decision making on strategic selection of wind farms, *Renewable Energy* **34**(1) (2009) 120-126.
9. T. Supriyasilp, K. Pongput, T. Boonyasirikul, Hydropower development priority using MCDM method, *Energy Policy* **37** (2009) 1866–1875.
10. J.J Wang, Y.Y. Jing, C.F. Zhang, X.T. Zhang and G.H. Shi, Integrated evaluation of distributed triple-generation systems using improved grey incidence approach, *Energy* **33** (2008) 1427–1437.
11. J.J Wang, Y.Y. Jing, C.F. Zhang, G.H. Shi and X.T. Zhang, A fuzzy multi-criteria decision-making model for trigeneration system, Energy Policy **36**(10) (2008) 3823-3832.
12. J.A. Quintero, M.I. Montoya, O.J. Sánchez, O.H. Giraldo, and C.A. Cardona, Fuel ethanol production from sugarcane and corn: Comparative analysis for a Colombian case, *Energy* **33**(3) (2008) 385-399.
13. S. Kon Lee, G. Mogi and J.W. Kim, The competitiveness of Korea as a developer of hydrogen energy technology: The AHP approach, *Energy Policy* **36**(4) (2008) 1284-1291.
14. S. Kon Lee, Y.J. Yoon and J.W. Kim, A study on making a long-term improvement in the national energy efficiency and GHG control plans by the AHP approach, *Energy Policy* **35**(5) (2007) 2862-2868.
15. N. Nagesha, P. Balachandra, Barriers to energy efficiency in small industry clusters: multicriteria-based prioritization using the analytic hierarchy process, *Energy* **31**(12) (2006)1633–1647.
16. S. Vashishtha and M. Ramachandran, Multicriteria evaluation of demand side management (DSM) implementation strategies in the Indian power sector, *Energy* **31** (2006) 2210–2225.
17. M.M. Kablan, Decision support for energy conservation promotion: an analytic hierarchy process approach, *Energy Policy* **32**(10) (2004) 1151-1158.
18. T. Kagazyo, K. Kaneko, M. Akai and K. Hijikata, Methodology and evaluation of priorities for energy and environmental research projects, Energy **22**(2–3) (1997) 121–129.
19. R. Ramanathan, L.S. Ganesh, Energy alternatives for lighting in households: An evaluation using an integrated goal programming-AHP model, *Energy* **20**(1) (1995) 63-72.
20. S. Önüt, U.R. Tuzkaya and N. Saadet, Multiple criteria evaluation of current energy resources for Turkish manufacturing industry, *Energy Conversion and Management* **49**(6) (2008) 1480-1492.
21. S. Ghafghazi, T. Sowlati, S. Sokhansanj and S. Melin, A multicriteria approach to evaluate district heating system options, *Applied Energy* (2009) doi:10.1016/j.apenergy.2009.06.021.
22. Y. Goletsis, J. Psarras, and J.E. Samouilidis, Project ranking in the Armenian energy sector using a multicriteria method for groups, *Annals of Operations Research* **120** (2003) 135–157.
23. M. Goumas and V. Lygerou, An extension of the PROMETHEE method for decision making in fuzzy environment: Ranking of alternative energy exploitation projects, *European Journal of Operational Research* **123** (2000) 606-613.
24. D.A. Haralambopoulos and H. Polatidis, Renewable energy projects: structuring a multicriteria group decision-making framework, *Renewable Energy* **28** (2003) 961–973.

25. G. Mavrotas, D. Diakoulaki and L. Papayannakis, An energy planning approach based on mixed 0-1 multiple objective linear programming, *International Transactions in Operational Research* **6** (1999) 231-244.
26. A.R. Borges and C.H. Antunes, A fuzzy multiple objective decision support model for energy-economy planning, *European Journal of Operational Research* **145** (2003) 304–316.
27. F. Cavallaro, Fuzzy TOPSIS approach for assessing thermal-energy storage in concentrated solar power (CSP) systems, *Applied Energy* **87(2)** 2010 496-503.
28. S. Kon Lee, G. Mogi and J.W. Kim, Decision support for prioritizing energy technologies against high oil prices: A fuzzy analytic hierarchy process approach, *Journal of Loss Prevention in the Process Industries* (2009) doi:10.1016/j.jlp.2009.07.001
29. Y.P. Cai, G.H. Huang, Z.F. Yang and Q. Tan,. Identification of optimal strategies for energy management systems planning under multiple uncertainties, *Applied Energy* **86** (2009) 480–495.
30. R. Lahdelma, S. Makkonen, P. Salminen, Two ways to handle dependent uncertainties in multi-criteria decision problems, *Omega* **37** (2009) 79 – 92.
31. N.H. Afgan and M.G. Carvalho, Sustainability assessment of a hybrid energy system, *Energy Policy* **36** (2008) 2903– 2910.
32. K.D. Patlitzianas, A. Pappa and J. Psarras, An information decision support system towards the formulation of a modern energy companies' environment, *Renewable and Sustainable Energy Reviews* **12** (2008) 790–806.
33. N.H. Afgan, P.A. Pilavachi and M.G. Carvalho, Multi-criteria evaluation of natural gas resources, *Energy Policy* **35** (2007) 704–713.
34. J. Burton and K. Hubacek, Is small beautiful? A multicriteria assessment of small-scale energy technology applications in local governments, *Energy Policy* **35** (2007) 6402–6412.
35. K.D. Patlitzianas, K. Ntotas, H. Doukas, and J. Psarras. Assessing the renewable energy producers' environment in EU accession member states, *Energy Conversion and Management* **48** (2007) 890–897.
36. H. Polatidis, D.A. Haralambopoulos, G. Munda and R. Vreeker, Selecting an appropriate multi-criteria decision analysis technique for renewable energy planning, *Energy Sources Part B* **1** (2006) 181–193.
37. P. Zhou, B.W. Ang, K.L. Poh (2006) Decision analysis in energy and environmental modeling: An update, Energy **31**(14) (2006) 2604-2622.
38. F. Cavallaro and L. Ciraolo, A multicriteria approach to evaluate wind energy plants on an Italian island, *Energy Policy* **33** (2005) 235–244.
39. S.D. Pohekar and M. Ramachandran, Application of multi-criteria decision making to sustainable energy planning—A review, *Renewable and Sustainable Energy Reviews* **8** (2004) 365–381.
40. Y.I. Topcu and F. Ulengin, Energy for the future: An integrated decision aid for the case of Turkey, Energy **29** (2004) 137–154.
41. H. Polatidis and D.A. Haralambopoulos, Local renewable energy planning: a participatory multi-criteria approach. *Energy Sources* **26** (2004)1253–1264.
42. M. Beccali, M. Cellura and M. Mistretta, Decision-making in energy planning: Application of the ELECTRE method at regional level for the diffusion of renewable energy technology, *Renewable Energy* **28** (2003) 2063–2087.
43. N.H. Afgan and M.G. Carvalho, Multi-criteria assessment of new and renewable energy power plants, *Energy* **27** (2002) 739–755.
44. S. Auephanwiriyakul, J.M. Keller, P.D. Gader, Generalized Choquet fuzzy integral fusion, *Information Fusion*, **3** (2002), 69–85.
45. H.H. Tsai and I.Y. Lu, The evaluation of service quality using generalized Choquet integral, *Information Sciences* **176**(6) (2006) 640-663.
46. M. Sugeno, *Theory of fuzzy integrals and its applications* (Ph.D. Thesis, Tokyo Institute of Technology, Tokyo, 1974).
47. K. Ishii and M. Sugeno, A model of human evaluation process using fuzzy integral, *International Journal of Man-Machine Studies* **22**(1) (1985) 19-38.
48. F. Begic and N.H. Afgan, Sustainability assessment tool for the decision making in selection of energy system-Bosnian case, *Energy* **32** (2007) 1979–1985.